2

AIR EJECTORS.

The desirability of providing separate means for extracting the air from condensers was not realised in early installations, and it was not until the development of the steam turbine stimulated the production of very high vacua that designers understood how such an omission caused air to accumulate in the condensers, with consequent reduction in both heat transmission and vacuum. A further loss ensued because the condensate itself formed the only vehicle for removing the air, and thus its temperature had to be undesirably (from the thermal standpoint) reduced in order to carry away a sufficient quantity in solution.

The dual air pump was an early attempt to meet the situation, being further improved by the use of steam air ejectors or vacuum augmentors. Increasing knowledge regarding the causes of corrosion in boilers, pointed clearly to the desirability of de-aerating the feed as far as possible, and this requirement sealed the doom of the dual air pump-cum-air ejector system, where the major part of the air extracted from the condensers is redissolved in the condensate. The Closed Feed System was then introduced mainly on account of its virtues in regard to de-aeration, and also because it forms a safe and convenient method of employing rotary feed pumps, with their attendant advantages as regards weight and space. This system is the first in which the extraction of the water and the air from the condenser are entirely distinct processes.

There are three types of pump suitable for the separate removal of the air from a condenser, namely, displacement, centrifugal and steam-jet (or air ejectors). The former two types are preferable from the point of view of thermal efficiency, especially when the steam exhausted from their prime movers can be used for feed heating: this advantage is somewhat reduced if the necessary cooling of air ejectors is performed by condensate instead of by sea water. It is, however, considered that the savings in weight and space rendered possible by use of the air ejector far outweigh, from the naval standpoint, any contingent loss in efficiency (which in any case is relatively small).

Air Cooling and Stage Inter-Coolers.—The size of any type of gas pump depends on the volume to be dealt with in unit time, and it is thus obvious that the size of pump required to extract a given weight of air at a certain vacuum will vary with the temperature (Charles law). Further, in the case of a condenser, the lower the temperature the smaller the weight of *vapour* that must be extracted with the air. For these reasons a certain proportion of the main condenser surface is specially allocated for air cooling or alternatively (as in some shore plants) separate coolers are fitted between the condenser and the air ejector suction.

The pressure drop across the cooling surface, together with considerations of weight and space, sets the upper limit to the amount of surface provided, 10 to 15 per cent. of the total condenser surface being an average figure in modern marine practice. The comparatively inefficient disposition of this surface, coupled with the low heat transmission resulting from the high proportion of air to vapour, prevents a large degree of air cooling being realised, but an air suction temperature some 10° F. below the condensate temperature should be obtained with the above proportion of surface.

Each stage of an air ejector is designed for an arbitrary compression ratio usually in the neighbourhood of 7 : 1, though in practice this may be varied considerably without any resulting instability. On this basis the theoretical maximum vacuum that can be realised by any number of stages in series is easily determined.

The air, or mixture of air and water vapour, has its temperature raised by adiabatic compression as it passes through each stage: this fact, together with the volume of steam added to the mixture by the jets, would necessitate a progressive increase in capacity from stage to stage. Inter-coolers are therefore fitted to condense the excess vapour and reduce the volume of the admitted air before passing to the suction of the next stage.

The first air ejectors in the service were 3-stage and had sea water cooled inter-coolers, which provided sufficient cooling with a comparatively small surface, by reason of the available temperature difference. The risk of feed water contamination due to tube leakage, coupled with the possible thermal gain, led to the adoption of condensate cooling. It is of interest to note in this connection that contamination of the feed with salt water may be experienced via the drains of even condensate-cooled air ejectors under certain unusual circumstances. Thus if a condenser develops a leak when not in use, the steam side may become flooded with sea water, which will eventually enter the ejectors through the air suction system, whence access can be obtained to the feed or reserve tanks. It is desirable, therefore, to keep sea inlets and discharges shut under such conditions; the air ejector drains should evidently never be neglected as possible sources of contamination.

Condensate cooling involves some reduction in temperature difference, as the condensate is on an average some 30° F. hotter than the sea water. Larger inter-cooler surfaces are thus necessary, but even so the first condensate cooled ejectors gave a poor performance on account of the small cooling capacity of their inter-coolers, and improvement was next obtained by two modifications, viz. :—

(1) Two stages instead of three, because a 3-stage ejector with its low first stage discharge pressure (and corresponding saturation temperature) requires a lower temperature of the cooling medium to obtain sufficient inter-condensation.

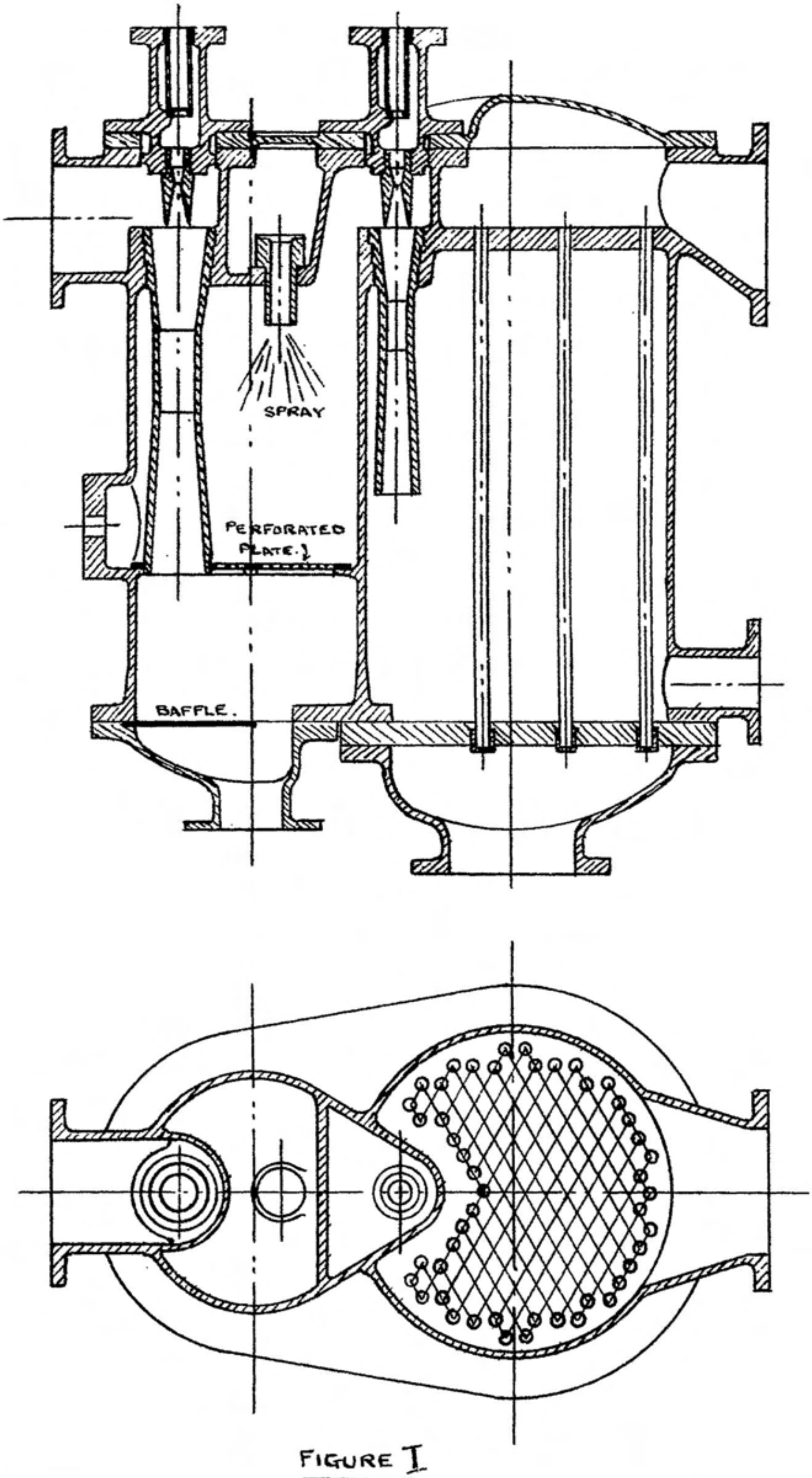

FIGURE I

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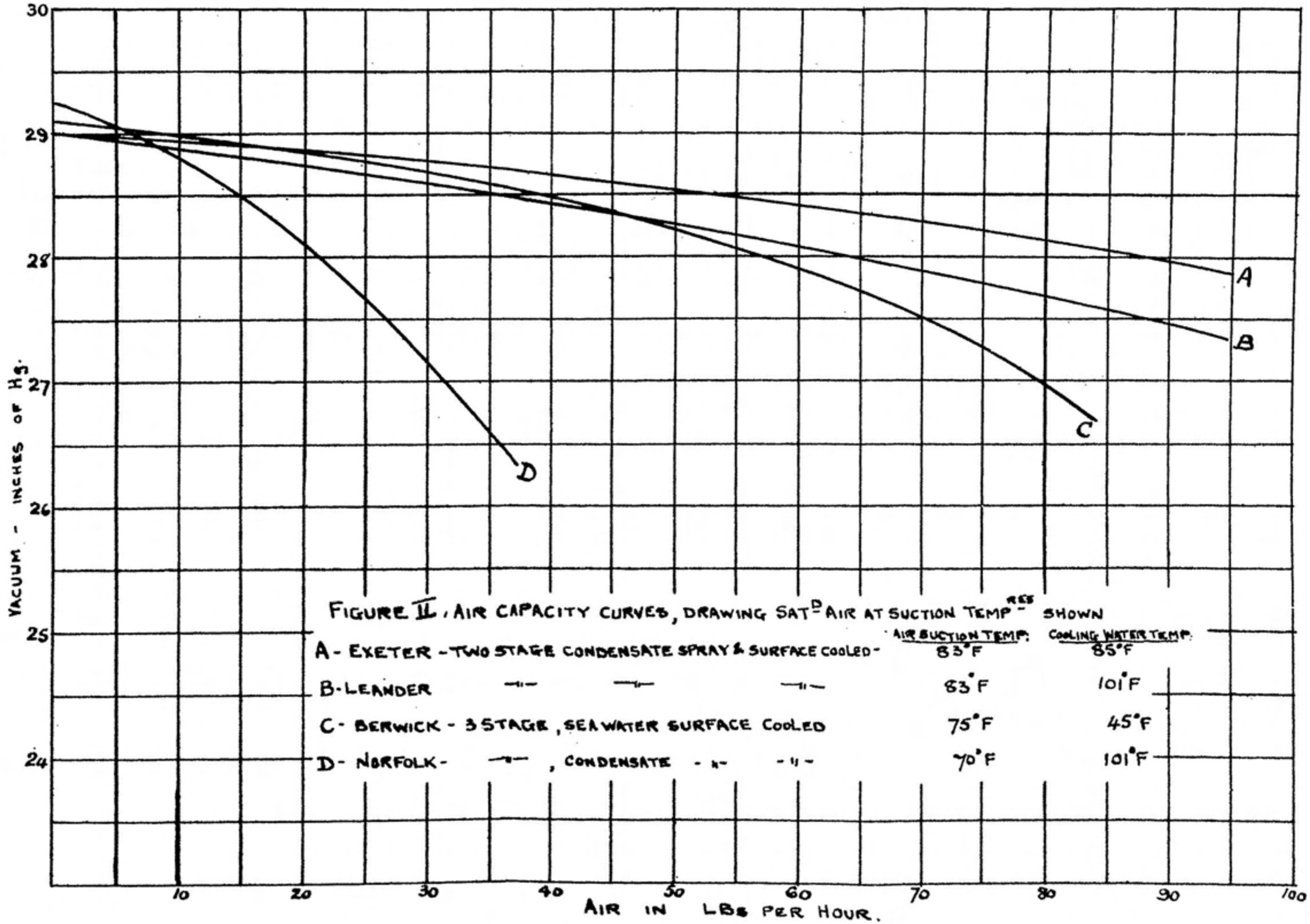

FIGURE II, AIR CAPACITY CURVES, DRAWING SAT^D AIR AT SUCTION TEMP^RES SHOWN

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(2) Spray cooling in lieu of or in addition to surface cooling between the stages.

The introduction of spray cooling so improved the performance as to warrant its retention in spite of the thermal loss, which is preferred to the alternative large increase of tube surface that would be required to obtain the same results.

Fig. I is a diagrammatic sketch of a 2-stage air ejector for a recent cruiser. The inter-cooler consists of a spray, while a surface after-cooler is fitted, the cooling medium being condensate in both cases. A light non-return valve, called the vacuum retaining valve, is fitted to the discharge from the second stage to prevent a sudden reversal of flow should the ejector cease to function for any reason.

The curves in Fig. II, taken from shop trial results, show the improvement effected by the previously mentioned modifications. Comparisons between B and D shows the advantage of spray inter-cooling with high condensate temperatures, while A and B or C and D show the effect of the temperature of the cooling medium on two ejectors of approximately similar design. It should be noted that when evacuating a steam condenser the ejector must deal with saturated vapour, and thus the slight advantage of three stages over two cannot be realised unless a low suction and cooling medium temperature can be obtained.

Ejector Capacity.—The question of the necessary ejector capacity for any particular condenser requires two assumptions in addition to the known data :—

(1) The anticipated air leakage in lb./hour.

(2) The air suction temperature in relation to the vacuum and condensate temperature which may be expected.

The Air Leakage will obviously depend on the number and condition of glands under vacuum, the aeration of the boiler feed and general " tightness " of the installation. A design rule of 1/2,000ths of the weight of steam condensed is sometimes quoted, but tests in a modern cruiser at full power gave approximately 25 lb./hr., or nearer 1/8,000th of the steam. This figure may be expected to be increased in time to, say, 50 lb./hr. by the normal accumulation of small leaks, etc.

The Amount of Air Cooling that may be expected has already been mentioned, but few condenser designers will predict confidently in this matter. From the air suction temperature and vacuum the proportion of air by weight in the mixture being dealt with by the ejector can be determined by the application of Dalton's law, and so, for the assumed air leakage, the mixture capacity of the first stage of the ejector determined. The second stage capacity can be determined in the same way, assuming a temperature drop through the inter-condenser.

The curve in Fig. 3 shows the percentage of weight of air in a saturated mixture of air and vapour at 28-in. vacuum and at different temperatures. It will be seen from this how important an effect the cooling " before" each stage has on the required capacity of that stage for a certain weight of air.

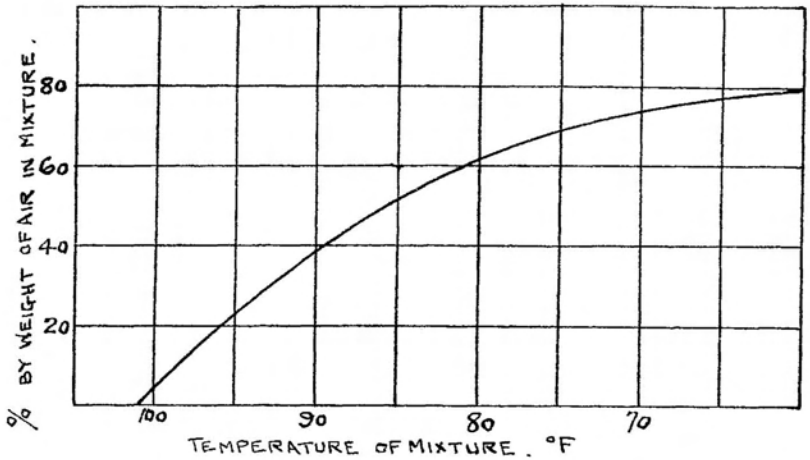

FIG. 3.

It may be remarked that at high vacua ejectors are found to have a slightly higher capacity when dealing with saturated air than that calculated from their dry air capacity corrected for temperature by Dalton's law; this gives a small margin if they are tested by measuring their dry air capacity, as was the case with earlier installations.

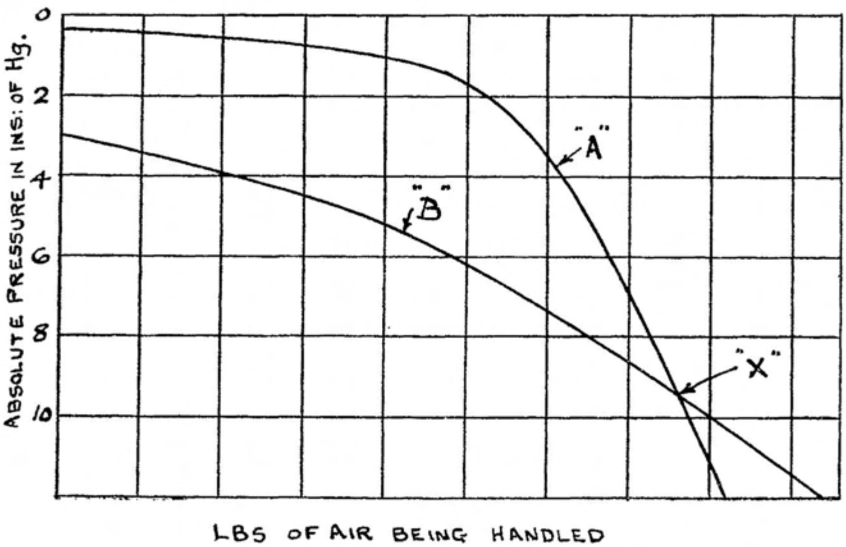

FIG. 4.

Fig. 4 shows two capacity curves for a two-stage ejector, viz. :—

(*a*) Both stages in operation.
(*b*) Second stage only in operation.

From this it will be seen that below a certain vacuum the capacity of the second stage alone is greater than both stages in series. This is due to the fact that as the vacuum is reduced, the departure from the designed conditions is more rapid in the first than in the second stage, because the discharge pressure from the latter is constant (atmospheric). Consequently the capacity of the first stage, and therefore necessarily that of the whole ejector, falls off until it is less than that obtained with the second stage alone.

The time required to raise a given vacuum depends, of course, upon the capacity of the air ejectors. It will thus be evident, from what has just been said, that the last stage of an air ejector should be used alone for raising up to and working at vacua of about 21 in. Hg (point X on Fig. 4). This point will, of course, vary in different designs of ejector, being dependent amongst other factors upon the air resistance of the circuit between the condenser and the inlet to the particular stage considered. It may, however, be readily determined in practice by artificially increasing the air leakage and finding when the second stage alone maintains a higher vacuum than both stages together.

Starting up with the first stage alone (or in conjunction with succeeding stages) is also liable to produce instability as the discharge pressure of this stage is then atmospheric, and thus is far removed from the designed condition. This practice is undoubtedly a not infrequent cause of failure to raise vacuum at the expected speed.

Testing Air Ejectors.—It is desirable for practical purposes to have available some method of testing the performance of Air Ejectors, mainly in order to determine whether the work of stripping them can profitably be undertaken. The ultimate test is, of course, that of measuring the actual quantity of air that the ejector is handling—this also provides a valuable check on the general air-tightness of the system.

Measurement of the Quantity of Air being extracted from a condenser can be carried out by means of a thin plate orifice and manometer fixed to the atmospheric discharge, as in Fig. 5.

The thermometer must be removed before taking the manometer reading, while the " after condenser " drain should also be closed. The curves in Fig. VI give the weight of dry air contained in the saturated mixture discharged from the orifice for various pressure differences with a temperature = 100° F., while Fig. VII gives a correction for variation in temperature of the air discharge.

It is, however, frequently desirable to ascertain whether the performance of an air ejector is up to standard. A rough indication may be obtained by running the unit with its suction valves shut off, observing the vacuum registered at the inlet to the first stage, and comparing it with that obtained on shop tests at zero capacity.

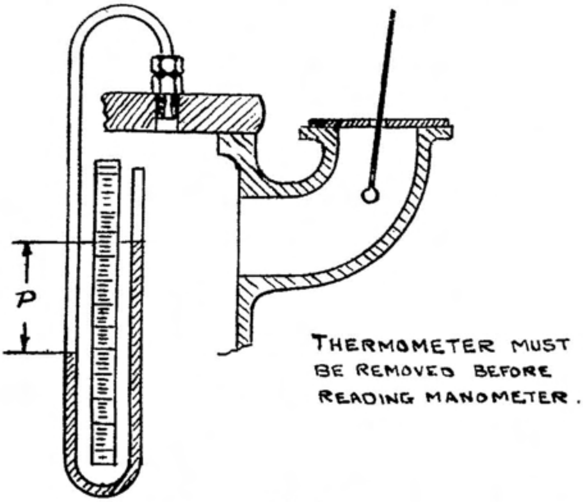

FIG. 5.

The state of efficiency of the ejector is best judged by the vacuum maintained at inlet to the first stage when drawing in air solely through an orifice of the same dimensions as that used on the shop tests of the air ejectors: information regarding the proper size of orifice can usually be taken from the drawings or from the report of the shop trials.

When carrying out tests to ascertain the performance of an ejector it is essential to measure the inlet and discharge temperatures of its cooling water, in order to take account of the effect of this factor and also to obtain an index of the state of the cooling arrangements.

Condition of Cooling Surfaces.—The importance of obtaining the maximum cooling effect from the arrangements provided cannot be overestimated, and it is probably not too much to say that the majority of practical troubles in connection with production of vacuum may be traced to this source. Much inconvenience will be avoided, while economy is furthered, if very frequent attention is given to washing out sludge, etc., deposited in the air ejector jackets: this applies with particular force to those provided with sea-water circulation. Heat transmission is greatly retarded by scale formation on the tubes; this may be appreciably reduced if a practice is made of maintaining the circulation of cooling water for sufficiently long after steam is shut off to cool the air ejectors down to engine-room temperature. It is also desirable in this connection to keep jackets drained when not in use. Air locking of part of

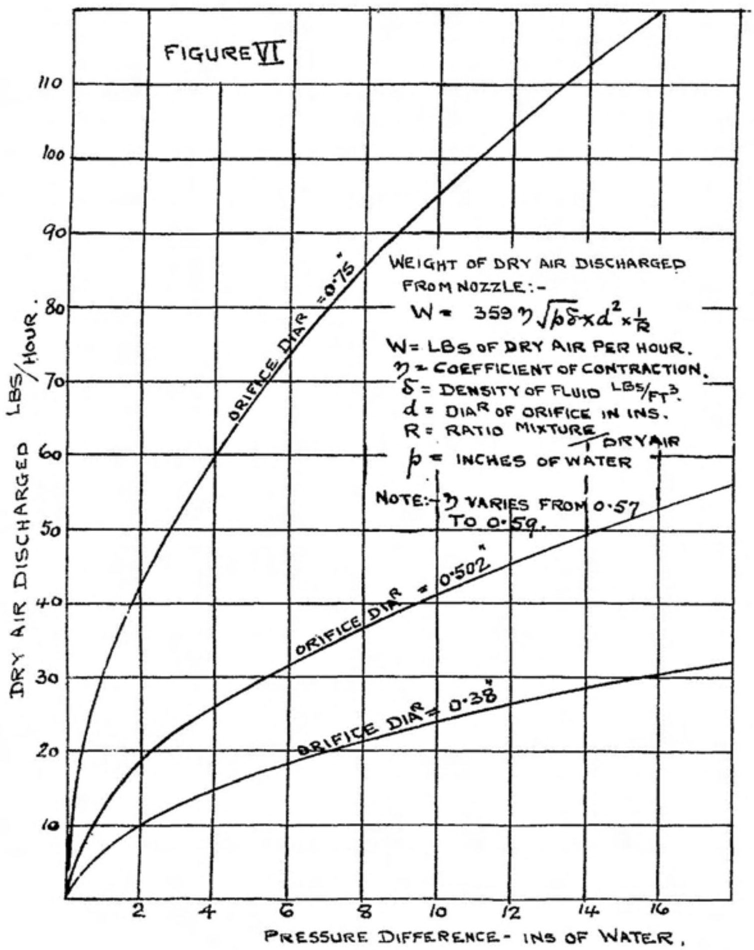
FIGURE VI
WEIGHT OF DRY AIR DISCHARGED FROM NOZZLE:-
W = 359 η √(pδ) × d² × 1/R
W = LBS OF DRY AIR PER HOUR.
η = COEFFICIENT OF CONTRACTION.
δ = DENSITY OF FLUID LBS/FT³.
d = DIAR OF ORIFICE IN INS.
R = RATIO MIXTURE / DRY AIR
p = INCHES OF WATER
NOTE:- η VARIES FROM 0·57 TO 0·59.
ORIFICE DIAR = 0·75"
ORIFICE DIAR = 0·502"
ORIFICE DIAR = 0·38"
DRY AIR DISCHARGED LBS/HOUR.
PRESSURE DIFFERENCE - INS OF WATER.
10
20
30
40
50
60
70
80
90
100
110
2
4
6
8
10
12
14
16

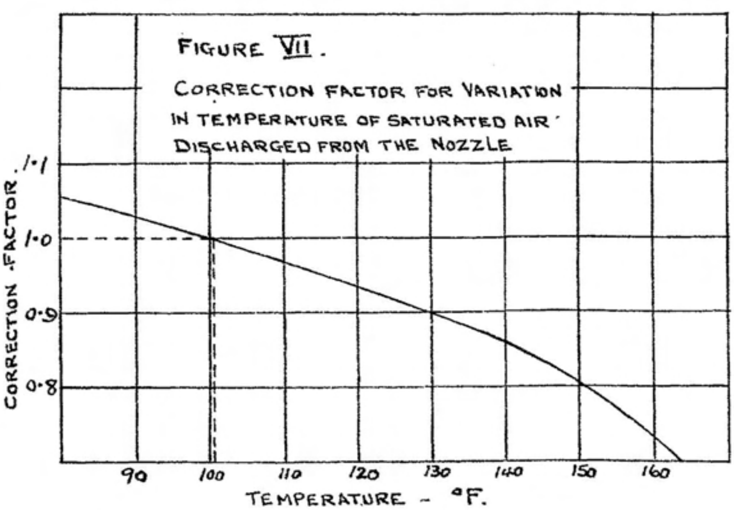
FIGURE VII.
CORRECTION FACTOR FOR VARIATION IN TEMPERATURE OF SATURATED AIR DISCHARGED FROM THE NOZZLE
CORRECTION FACTOR.
TEMPERATURE - °F.
0·8
0·9
1·0
1·1
90
100
110
120
130
140
150
160

the cooling surface is common, especially in those designs where the cooling water discharge pipe is not attached to the extreme upper point of the jacket (Fig. 8). It will frequently be found that the

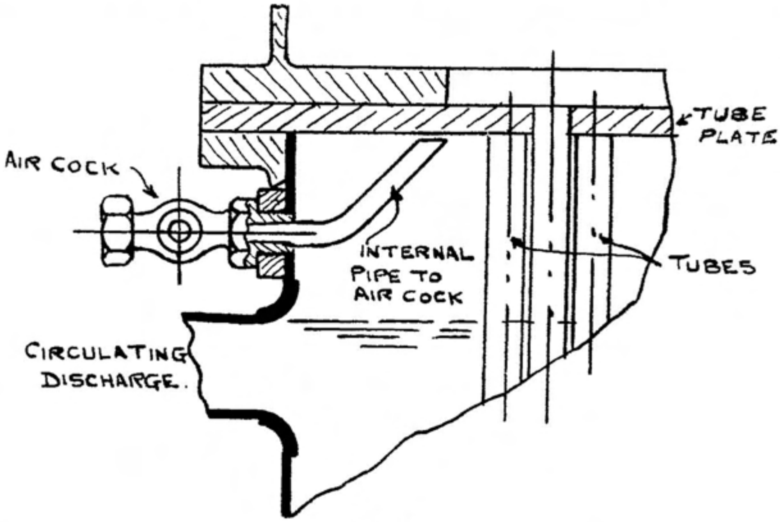

FIG. 8.

air cocks are originally fitted so that complete evacuation of the air from the jackets is impossible; a small internal extension of the air cock on the lines indicated in Fig. 8 will be found of service in this connection.

A reduced water supply is not infrequently due to the partial closure of the cooling water pipes by the swelling of the protection pieces as they become converted to oxide; this is particularly noticeable in the case of cylindrical protection pieces forming part of the water circuit.

Number of Air Ejectors in Use—Effect on Economy.—The decision whether it is better to increase the number of air ejectors in use with a view to improving the vacuum or to be satisfied with a higher condenser pressure in order to save the steam consumption of additional ejectors, is of course a matter for local experiment and depends to some extent upon the design of the turbines. It may, however, be stated with some confidence that, if the use of another ejector noticeably improves the vacuum it will also result in increased economy in most naval installations, even where salt-water cooling is employed and the majority of the heat in the ejector steam thereby wasted. Thus in a modern cruiser an improvement of only 1/10-inch in vacuum under normal cruising conditions may be expected to give a reduction on fuel consumption of nearly 1 per cent.; the fuel consumption of one air ejector under these circumstances is about one-half of 1 per cent. of the total expenditure, being, of course, an even smaller percentage at higher powers. The actual steam consumption of the air ejectors varies with the steam pressure, Fig. 9 showing a typical case. It may be

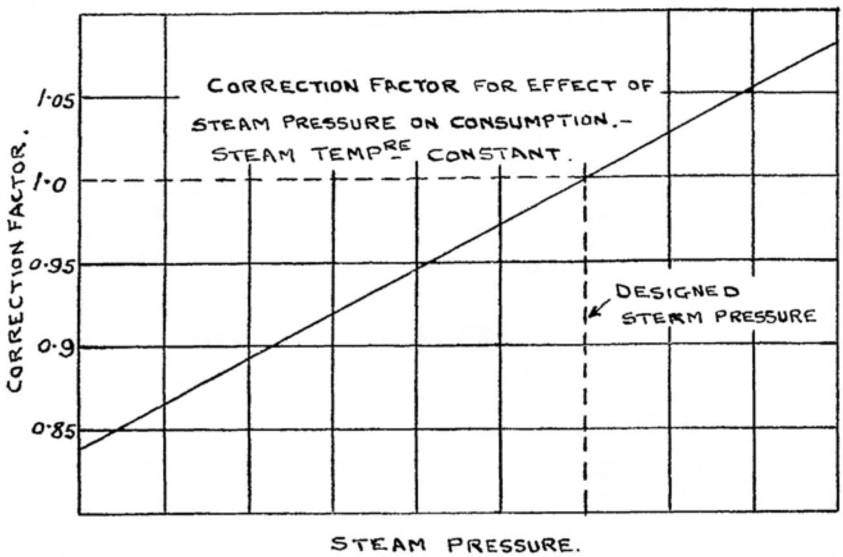

FIG. 9.

observed that variation from the designed steam pressure usually causes a reduction in the air handling capacity. Under conditions of reduced vacuum and high air leakage an increase of steam pressure at the first stage may, however, give a slight improvement; thus, where such is found to be the case, it should be taken as an indication that the ejector is not operating under its designed condition, and the cause should be investigated.

Condition of the Jets.—The condition of the jets may have a considerable bearing upon the efficiency of the ejector. In practice the throats should be kept smooth and at their designed dimensions: this is best done by occasionally passing through them by hand a small twist drill, ground specially to the exact diameter indicated on the drawings. Although it is not possible to state the extent to which malformation will reduce efficiency, it is obviously good practice to keep the exit edges in good condition and free from burrs.

Multiple jets were used in the earlier injectors, but it is now known that a single jet of similar capacity is equally effective, while possessing the merit of reduced liability to choking.